A pplication of SAR Remote Sensing in Land Surface Processes Over Tropical Region

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Abstract. Spat.c.borl]c SAR (Synthetic Aperture Radar) systems and related programs currently envisioned by the international science community provide an important framework for addressing key science issues and applications inland surface processes. The models that simulate these processes require surface parameters such as vegetat ion structure and biomass, land cover, soil and canopy moisture that SAR measurements being sensitive to surface geomerty and dielectric properties Can provide. This paper outlines the potential applications of polarimetric SAR systems over tropical regions such as mapping land USC. and deforestation, forest regeneration, wetland and inundation studies, and mapping land cover types for biodiversity and habitat conservation studies.

Keywords: SAR, Polarimetry, Land Use, Biomass, Moisture

1. introduction

At present, se veral interdisc iplinary studies around the world arc concentrated on understanding the processes that govern the interaction of the land surface with the atmosphere and the changes that are occur ring in both, primarily as a result of human activities. These processes arc modeled at diffc.rent scale.s require parameterization of the land surface to be included eventually in the climate models. Although climate models require. global specification of land properties on a spatial scale of 25 -50 km, sub-grid models dealing with the sur face hetrogeneity may require parametric inputs of finer spatial resolution (Dickinson, 1995). These parameters are fundamentall y used as controlling variables in land-atmosphere carbon, energy, and waler exchange models that characterize the. thermodynamic, chemical, and biological processes involved in the interaction between the land surface and the lower atmosphere (Hall, et al., 1995). The general categories of parameter inputs consists of vegetation and soil parameters, among them, land vegetation cover, community composition, vegetation structure such as leaf area index, biomass density, phenology, vegetation condition, primary productivity, canopy roughness, and soil moisture. Remote sensing techniques are beginning 10 play an important role in providing these parameters on global and regional scales and 10 contribute in improving and validating{ these models.

Tropical forests, because of the large area of land surface they cover (about 1 600 million hectares at the climatic climax), their humid climate (rainfalls of above 20(N mm per year), and being the most luxuriant and species-rich forests are responsible for the major propor lion of the ear lb's biological productivity. This represents a vast yearly intake of the CO_2 which is stored in the tree.'s tissues. A large number of ecological studies conclude that the conversion of this ecosystem is realiz ing a as much CO_2 in the atmosphere as were the industrial processes (Detwiller and hall, 1988). Reducing the uncertainty in estimating the release of CO_2 requires an accurate estimate of the deforested and new regrowth areas. Monitoring and mapping the land usc change in tropical region, ttmc.fore, is still a challenging scientific problem. Deforestation of the tropical rain forest and its conversion to other land cover types such as pasture introduces several other scientific problems to be tackled. For example, the dynamics of the conversion of forest to pasture, agricultural crops and forest regeneration that in turn affects the potential of the land for sustainable production of food and protein. Deforestation in the entire tropical belt, encompassing Africa, Asia, Central and South America is estimated to bc 42% of the total moist tropical fore.sl (Buschbacher, 1 986). Chc.eking the accuracy of this estimate is hindered by insufficient database and remote sensing techniques are the main source of providing the required database.

The hydrological problem associated with the river basins in tropics such as in the Amazon rainforest, also requires information about the dynamic of land use. change and its impact on the routing of water and its chemical load from precipitation input through the drainage system back to atmosphere and 10 the ocean. Remote sensing techniques can provide information such as land use. change, surface soil moisture and fore.st inundation dynamics that can be used directly in the tropical river catchment studies (Richey, et al., 1989). Furthermore, in studies related 10 biogenic trace gas exchange, the knowledge of type and distribution of wetlands and the temporal distribution of inundation in tropical region can reduce the uncertainties due to spatial and seasonal extend of the methane source and sink areas. Several other issues such as the increasing rise of insect related (li sease outbreaks in tropical wetlands are correlated with rainfall events and flooding episodes and the type of vegetation cover (herbaceous and woody vegetation)that can be monitored with remote sensing techniques (Hess, et al., 1995, Pope, et al., 1994).

In this paper, we attempt to demonstrate the potential application of radar remote sensing in the above mentioned processes. The data presented in this study are taken from a series of experiments involving airborne and spaceborne systems over the tropical ecosystems in South America. The characteristics of polarimetric SAR systems and the factors that affect SAR backscatter measurements are described in section ?. In sections 3 [0 6, several examples pertaining 10 land surface process studies are discussed and references are provided for further discussion and approaches.

2. SAR Polarimetry

Radar remote sensing instruments operate in microwave region of the electromagnetic spectrum where the atmospheric interference is minimum and the waler vapor column and cloud cover do not affect the propagation of the radar signal. Because radar furnishes its own illumination, images could be obtained either during the day or night, a considerable advantage over optical sensors that depend on the sun as the light source or obscured by the presence of Clouds. in the past two decade, radar systems have evolved from a real aperture single. frequency and polarization system, to synthetic aperture (SAR), polarimetric systems operating at various wavelengths, providing measurements of wavelenglh-scale geometrical and polarization properties of the surface in the form of high resolution images. Polarimetric SAR systems allow measurements of the amplitude and relative phase of all JJolari7.alien configurations of the transmit and receive ante.nnas for all independent resolution elements in a scene (Ulaby and Elachi, 1990). A typical polarimeter is configured such that it uses the horizontally and vertically polarized antennas to achieve the polarization diversity by measuring the true scattering matrix of a resolution element. From the scattering matrix measurements, the Stokes matrix that relates the transmitting and receiving wave intensities are formed. 'The quantity that is often used 10 characterize the resolution element is referred as backscattering coefficient and is defined by the radar equation as the effective scattering area subtended by the scatterer divided by tile resolution area. in what follows, we use H as horizontal polarization and V as vertical polarization of either transmit or received antennas. Therefore the backscattering coefficient are measured in HH, HV, VH, and VV polarizations that refer [0 the combinations of transmit and received polarizations (1 IV and V} I are equal in backscattered direction).

Polarimetric measurements permit belter identification of the scattering mechanisms that in turn help resolve lilt electrical and geometrical properties of the surface (Figure 1). Depending on the wavelength of the system, the. penetration depth of the radar signal through vegetation and soil surface varies, allowing stratification of the geometrical properties of the land surfaces, Overall the information embedded in the polarimetric multifrequency SAR data can be related 10 three major categories of parameters of the land surfaces: geometry, penetration, and moisture. Looking al forests, the backscatter measurements related to several scattering mechanisms such as direct backscatering from crown (branch and leaves), crown-ground scattering, trunk-ground scattering and the direct scattering from the forest floor. The significance of these mechanisms vary in different polarization configurations.

Several spaceborne and airborne SAR systems are used in land surface, applications. The airborne. JPL AIRSAR system has three frequencies P-band (60 cm wavelength), L-band(24 cm wavelength), and C-band (6 cm wavelength) and operates in fully polarimetric mode. The SIR-C/X-SAR system has L-, and C-band polarimetric and X- band (3 cm wavelength) VV polarization and was used in two ten day missions in April and October of 1994 aboard the Space Shuttle Endeavor. in addition, currently there are three. orbital radar systems: the European ERS- 1 system (at C-band V V polarization), the Japanese JERS- 1 system (L-band HH polarization), and the Canadian RADARSAT system (C-band HH). Image data avail able from these instruments have been used in several studies to demonstrate their unique applications in land surface processes in tropics. Although, these, studies are by no means perfect and many factors that contribute to the. radar backscatter from soil and vegetation are yet to be fully explored, the result.s obtained so far indicate, that the signal penetration through forest canopy and its sensitivity to vege tation moisture and morphology are relevant to any future studies of the tropical biosphere.

3. Land Use and Deforestation

The causes of deforestation and land use change in tropical region depend on several factors among them the colonization programs, legal systems of tenure, relation of natural resources such as timber and production systems 10 economic and social variables, Recent estimation of the rate of deforestation in Amazonia implies that the.convulsion of forest to pasture and agricultural crops has a rapid pace. By 1991, the total area of Brazilian Amazon reached 426,000 km^2 with annual rate of approximately 22,000" km^2 over 1978-1988 and 14,000 km^2 in 1989-1990 and 19,000 km^2 for 1990-1991 (Fearnside, 1993). These figures imply that the process of deforestation is dynamic and any monitoring techniques must be accurate and frequent. The main source of deforestation studies over Amazon basin has been the Landsat imagery (Skole and Tucker, 1993; INPE, 1992). Despite exalting results from Landsat data, difficulties of obtaining more frequent data over areas where continuous cloud cover obscures the ground and inconsistent means of delineating secondary forest from primary forest and/or from various practices of forest disturbance.s suggest that accurate land use and de.forestation mapping is still a major scientific challenge, Other regions of the tropical rainforests such as Africa and Asia are yet to be mapped routinely.

Space.borne radar systems are potential tools for resolving some of the ambiguities in optical remote sensing techniques. The first contiguous mapping of vegetation and land use in the Brazilian Amazon was performed by the RADAMBRAZII, using an airborne X-band radar system supported by extensive field surveys. A recent study using the SIR-C polarimetric data over Rondonia has shown that polarimetric radar systems at L-band (1.25 GHz) and C-band (5.3 GHz) with HH and HV polarizations are successful in separating forest and non forest and fur[herlnoredcline.sting land use practices and forest regeneration (Saatchi, et al., 1996a). Figure 2 shows the results from this study. Using the four channels of the SIR-C data, five class types of primary fore.st, secondary regrowth, disturbed forest, quebradao, and pasture/crops with 72% accuracy. When the classes were reduced to three and only L-band polarimetric data were used, the accuracy of classification increased to 94%. The classification was based on the statistics of the backscatter data using a maximum *a posteriori* Bayesian classifier. The sensitivity of the HH and HV polarized backscattering coefficients to biomass and vegetation structure and moisture were among the main reasons for identifying the land cover classes.

It has also been demonstrated that for routine.ly estimating the rate of deforestation, a single polarization low frequency radar system such as JERS-1 (L-band, HH polarization) may be sufficient (Saatchi, et al., 1996b). Figure 3 shows a mosaic of the JERS-1 images over Rondonia that has been classified into forest and non-forest using SAR backscatter and texture information. Currently, JERS-1 satellite is engaged in mapping rainforests over three continents of South America, Africa, and Asia that can improve the. current estimates of the areas of fore.st and de forested land surface.s in the tropics.

4. Biomass Regeneration

Secondary forests c.over more. than 600 million hectares of tropical rainforest. The fore.st regeneration are. created by both natural causes and human activity. After the forest is cleared for pasture., crop cultivation or timber, the process of succession begin shortly after the land is abandoned. The early stages of succession are characterized by a very dense undergrowth with weedy herbaceous plants and fast growing vine.s, The rapid growing of early colonizers are due to seed distribution in the soil immediately after disturbance.. During this period, several forest structural attributes such as biomass and leaf area index increase rapidly that make the secondary re.generation a viable area to be detected by remote sensing techniques (Foody and Curran, 1994). One study shows that the leaf area index and woody biomass reach a maximum after about 20 and 40 years respectively (Brown and Lugo, 1990). The lack knowledge of the. process of deforestation and fore.st regrowth in a large scale arc the main sources of uncertainty in estimating the rate of the CO_2 exchange of terrestrial biota with the atmosphere. SAR systems operating at low frequency appear to be the only tool available for estimating the biomass distribution. Several studies over boreal and temperate forests have demonstrated that the capability of SAR systems for measuring biomass is approximately 200" inns/ha at P-band, 1()() tons/ha at L-band, and 50 tons/ha at C-band. Since most secondary forests up to 20 years of age do not necessarily have woody biomass values exceeding 100 tons/ha, the. SAR systems can improve the estimation of the biomass regrowth in the tropical forests (Figure 4).

The analysis of airborne SAR data over primary forests in Manu National Park in Peru shows that at P-band wavelength, HV polarization is correlated with the, branch biomass, whereas }1}1 channel is correlated with stem biomass (Rignot, et al., 1995). In a similar study, the analysis of the SIR-C data over Tapajos National Forest in Para, Brazil shows that at L-band, 1 IV polarization has the highest sensitivity 10 fore.sl regrowth up 10 9 years old (Yannse et al., 1996). Figure 5 illustrates the biomass variation over the Tapajos secondary forests by employing a biomass estimation algorithm that has been developed from forest backscatter modeling (Saatchi and Moghaddam, 1996). Further studies arc required 10 understand the sensitivity and limitations Or SAR measurements to biomass re growth in tropics. Nevertheless, the limited studies performed so far impl ics that P-band polarimetric data correlate better with biomass regeneration than L-band. However, L-band polarimetric systems appear to be more operational than P-band in near future.

5. Forest Inundation

The large river basin and the. periodic heavy rainy seasons responsible for the rise and fail of the river level, create large areas of inundated forest types in the tropics. These forests are distinct because oft heir limited diversity as compared to upland forests duc to the stress caused by the waterlogging of their root systems. Inundated forest types arc often divided into the permanent swamp fore.s[s(c.g, permanent white water and black waler swamps, igapo), periodically flooded forests (e.g. mangrove, seasonal varzea and igapo, tidal swamp), and gallery forests. Information on distribution, morphometry, and the areal extend of these forests is important in the regulation of water balance and biogeochemical cycle, and trace gas exchanges such as methane. In addition, these areas arc important for supporting fisheries and cultivation because of the relatively fertile soil left from the river sed i men [s.

Polarimetric backscatter measurements at L-band and C-band can be used operationally to map floodplains and forest inundation because of the penetration of the signal into the vegetation layer. Results from the SIR-C/X-SAR experiment shows that using radar can accurately delineate the herbaceous versus woody and flooded versus non- flooded cover types present in the Amazon river basin, Figure 6 shows the radar mapping of forest inundation in April (rainy season) and October (dry season). The results indicate that 1,11} I accurately separated flooded ver sus non flooded forests, cl]}] provided the best separation between flooded and non flooded herbaceous vegetation, and LHV distinguished well between woody and nonwoody vegetation (Hess et al., 1995). Application of SAR systems in many ecological and biogeochemical studies of wetlands and floodplains has shown that polarimetric measurements provide a suitable tool for mapping various types if forest inundation (Pope, 1994, Melack, et al., 1 994).

6. Biodiversity and Conservation

In recent years, satellite remote sensing has also been used in regional conservation and biodiversity studies worldwide. Deforestation and forest disturbance as a result of the expansion of human populations and human activities are the main cause of decay in organic diversity. in particular, tropical rainforests as being the most biologically diverse ecosystems, the conversion of primary biome has caused the degradation Or fore.sl habitats the concentration of species. This process is by no means even and some areas of the tropics are being affected harder than others (Myers, 1988). For example, the Atlantic forest that once occupied as area of more than onc million square kilometers along Brazi l's coast, is reduced to less than 9% of its original size because of colonization, mining, and extensive agricultural and urban development. The remaining fore.s[, much of which is concentrated in the state of Bahia is highly fragmented and the populations of threatened species arc in many cases reduced to very low number of individuals (Saatchi, et al., 1994). Local and international government and non-government organizations arc initiating conservation efforts, such as land protection and land purchase 10 enlarge the federal biological reserves such as Una in Bahia. These efforts arc. limited by lack of information about the locations of priority sites for conservation purposes. High resolution remote sensing data that can help identify vegetation types in these regions are the main source of information.

During SIR-C/X-SAR mission in October of 1994, polarimetric SAR data have acquired over the Atlantic coastal fore.s[of Bahia in support of conservation activities around the Una biological reserve located in southern Bahia. SIR-C data complemented the optical remote sensing data for mapping the primary patches of forest by providing information about the sub-canopy that helped discriminating forest from cocoa plantations and mangrove that was previously unavailable from optical data. The results of the analysis indicates that L-band HV polarization backscatter from large. canopy elements such as branches and leaves and corr elates with areas of high biomass. Areas of pasture and young secondary forest growth have higher backscatter at C-band HV polarization. In cocoa plantations (cabruca forests), the canopy is thinned and understory vegetation is rc.moved and replaced by sub-canopy cocoa. This causes a slight reduction in tree bole biomass (reducing L-band backscatter) and an increase in branch and foliage density in the sub-canopy (increasing C-band back scatter). The areas of mangrove swamp along the Atlantic coast has higher backscatter in all the channel s Of SAR data due to scattering Of the SAR signal from the underlying standing waler. 'J 'hese areas do not appear clearl y in the Landsat imagery (Saatchi, el a].,]994). These di fferences in radar signals duc 10 land cove.r types produce a different texture and backscattering coefficients that can be used to identify patches of pr imary forest for conservation practices. Figure 7 shows the preliminary results of mapping primary forest patches using a texture and backscatter data in a supervised Bayesian classifie r.

7. Conclusion

in this paper, the potential applications of polarimetric radar backscatter measurements in studying land surface. processes in the tropical forest ecosystems were briefly reviewed. It was shown that polarimetric and multifrequency measurements of the tropical vegetation provide information about the structure of forest and its moisture status that help classify the radar images into land cover types, separate deforested and forested areas, monitor and map wetlands and inundated areas, and monitor and estimate forest biomass regeneration. The examples were take.n mainly from the data collected by the SIR-C/X-SAR system in 1994. The results also demonstrate that the temporal frequency of calibrated SAR data over tropics suggest that it can monitor the dynamics Of land usc change better than optical sensor's in this region. However, accurate land cover classification maps are often achieved if both sensors are used in synergism, Furthermore, the forest regenerated biomass can be estimated by lower frequency polarimetric data (P- and L-band) that are not currently available in space. It is expected that as polarimetric spaceborne systems become operational in future, SAR imagery may become an invaluable source of information over tropics.

References

Brown, S. and Lugo, A.E., Tropical secondary forests, *J. Tropical Ecology*, vol. 6, 1-32, 1990.

Buschbacher, R. J., Tropical deforestation and pasture development, *Bioscience,* vol. 36, 22-28, 1986.

Detwiller, R.P. and Hall, C, A. S., Tropical forests and the global carbon cycle, *science*, vol. 239, 42-47, 1988.

Dickinson, R.E., l and processed in climate models, *Remote Sensing of Environ. vol. 51,* 27-38, 1995.

Fearnside, P. M., Deforestation in Brazilian Amazonia: The effect Of population and land tenure, *Ambio, vol. 22, 537-545,* 1993.

Hall, F.G., Townshend, J.R., and Engman, E.T., Status of remote sensing algorithms for estimation of land surface state parameters, *Remote Sensing of Environ.* VOl. 51, 138-156, 1995.

Hess, L.L., Melack, J. M., Filoso, S., and Wang, Y., Mapping wetland hydrology with synthetic aperture radar, *IEEE Trans. geosci. Remote Sens. 33, 896-904, 1995.*

Instituto Nacional de Pesquisas Espaciais (INPE), *Deforestation in Brazilian Amazonia*, INPE, *Sao* Jose. Dos Campos, Brazil, 1992.

Melack, J. M., Hess, L.L., and Sippel, S., Remote sensing of lakes and flood plains in the Amazon basin, *Remote Sens. Rev.*, vol. IO, *1?7-]42, 1994.*

Myers, N., Tropical forest species and their spc.tics, going, going....?, in *biodiversity*, edited by E.). Wilson, National Academy Press, Washington, DC, 28-35, 1988.

Pope, K. O., Rey-Benayas, J. M., and Paris, J.F., Radar remote sensing of fore.sl and wetland ecosystems in the Central American tropics, *Remote Sens. environ. vol. 48, 205-219, 1994.*

Richey, J.E., Adams, J.B., and Victoria, R.L., Synoptic-scale hydrological and biogeochemical cycles in the Amazon river basin: a modeling and remote sensing perspective, in *Remote Sensing of Biosphere Functioning*, eds. R.J. Hobbs and H.A. Mooney, Springer-Verlag, New York, NY, 1989.

Rignot, E. J., Zimmermann, R., and van Zyl, J. J., Spaceborne applications of P band imaging radars fore. measuring forest biomass, *IEEE* irons. *Geosci. Remote Sens. vol.* 33, 1162-1169, 1995.

Saatchi, S. S., Dietz, J., Rice, R., DeFries, Lawrence, W., Dietz, L. A., Araujo, M. S., and Alger, K., Shuttle imaging radar advances tropical forest conservation , JPL Report, Pasadena, California, 1994.

Saatchi, S. S., Soares, J. V., and Alves, D. S., Mapping deforestation and land use in Amazon rainforest using SIR-C imagery, submitted 10 *Remote Sens. Environ.* , February,1996a.

Saatchi, S. S., et al., Mapping deforestation in Rondonia, Brazil using JERS-1 mosaic data, submitted to *Ambio*, 1996a.

Saatchi, S.S. and Moghaddam, M., Biomass distribution in boreal forest using SAR imagery, Proceeding of EUROPTO, 26-30 September, 1994, Rome, Italy, vol. ?.314, 437-448, 1994.

Skole, D.L,. and Tucker, C.J., Tropical deforestation and habitat fragmentation in the Amazon: Satellite data from 1978 to 1988, *science, vol.* '2460, 1905-1910, 1993.

Ulaby, F.T. and Elachi, C., *Radar Polarimetry for Geoscience Applications*, Artech House, Norwood, MA, 1990.

Yanasse, C., Sant'Anna, S.J.S., Frery, A.C., Renno, C.D., Soares, J, V., and Luckman, A. J., SIR-C data dependence on tropical forest regeneration stages, submitted to *Remote Sensing of Environ.*, February, 1996.

Figure Caption

Fig. 1. Penetration capability of radar systems through vegetation.

Fig. 2. SIR-C derived land use map of a silt in Rondonia, Brazil. The cover types arc primary fore.sl, secondary regrowth, disturbed forest, quebradao, and pmturc/c.reps (Saatchi, et al., 1996).

Fig. 3. Deforestation map of Rondonia derived from JERS-1 mosaic in 1993-1994. The smaple image was taken from an area north of Ouro Preto.

Fig, 4. Biomass regrowth of leaves, roots and wood of different aged secondary forests in tropical forests (Brown and Lugo, 1990).

Fig. 5. Biomass variations of secondary regrowth in Tapajos National Park.

Fig. 6. SIR-C classified image.s of form inundation of Amazon rive.r basin in April and October (Hess, et al., 1995).

Fig. 7 SIR-C L-band and C-band color composite image of Una biological reserve in southern Bahia and the classified map of primary fore.st.

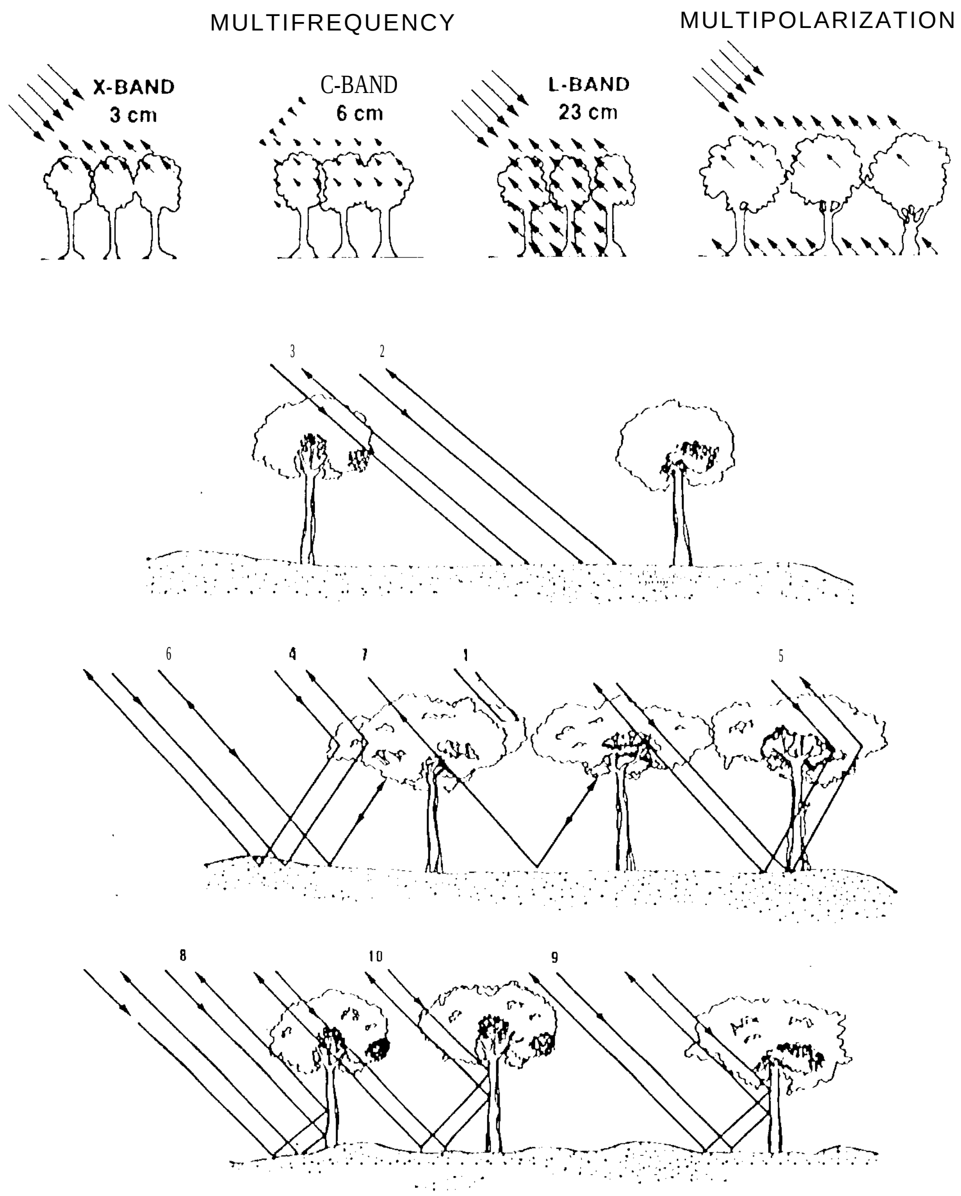
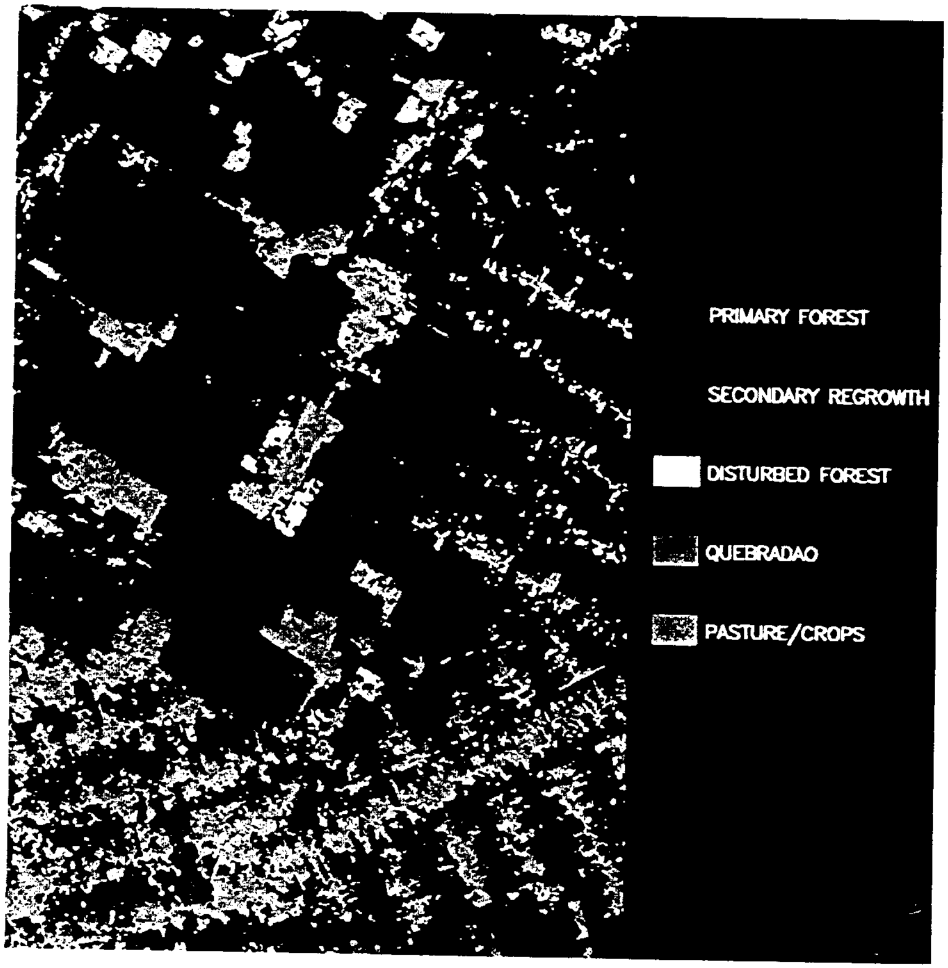
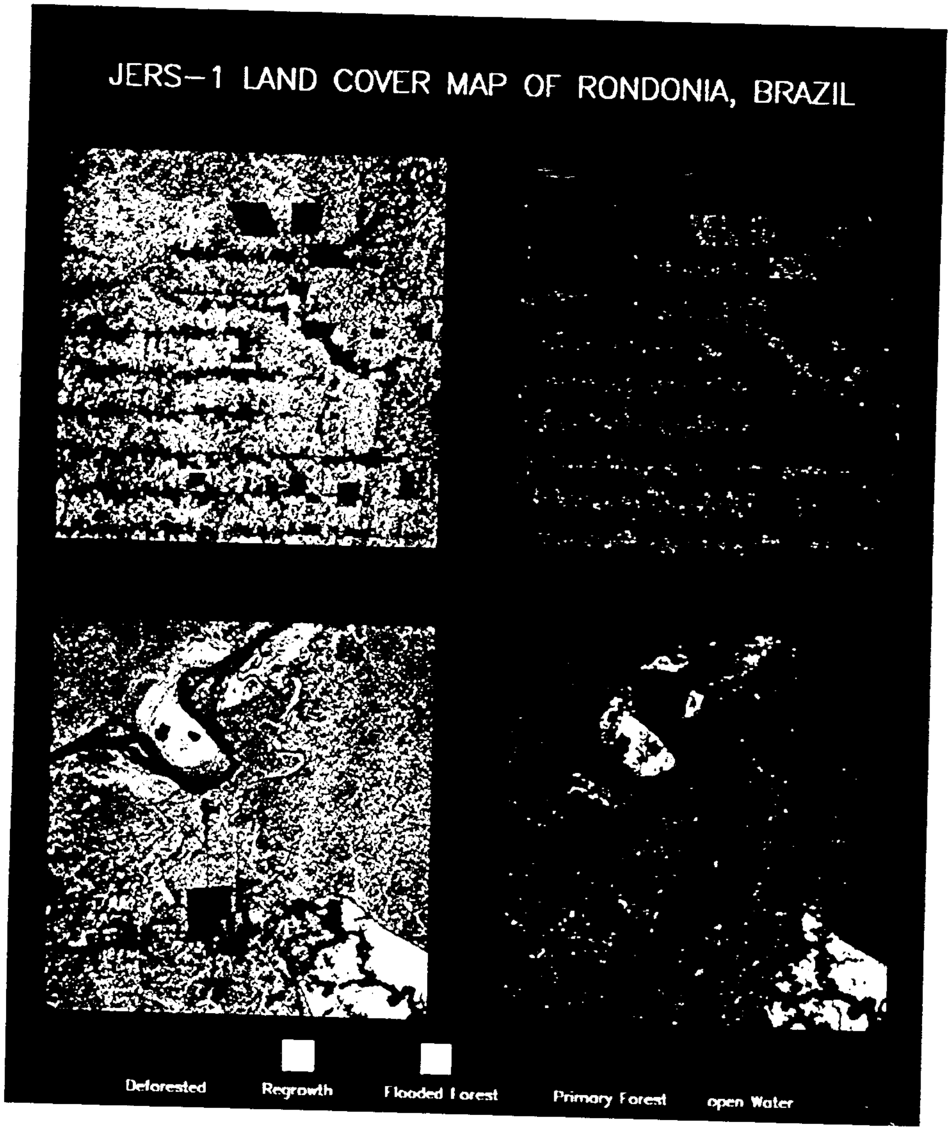


Fig. 1. Penetration capability of radar systems through vegetation and the interaction of radar signal with canopy components through various scattering mechanisms.


PRIMARY FOREST
SECONDARY REGROWTH
DISTURBED FOREST
QUEBRADAO
PASTURE/CROPS


JERS-1 LAND COVER MAP OF RONDONIA, BRAZIL
Deforested
Regrowth
Flooded Forest
Primary Forest
open Water

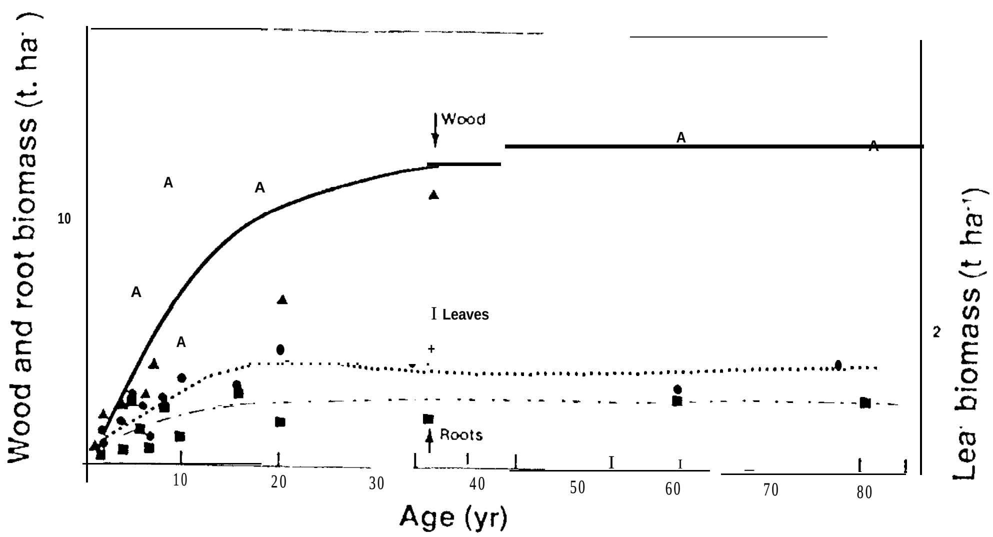
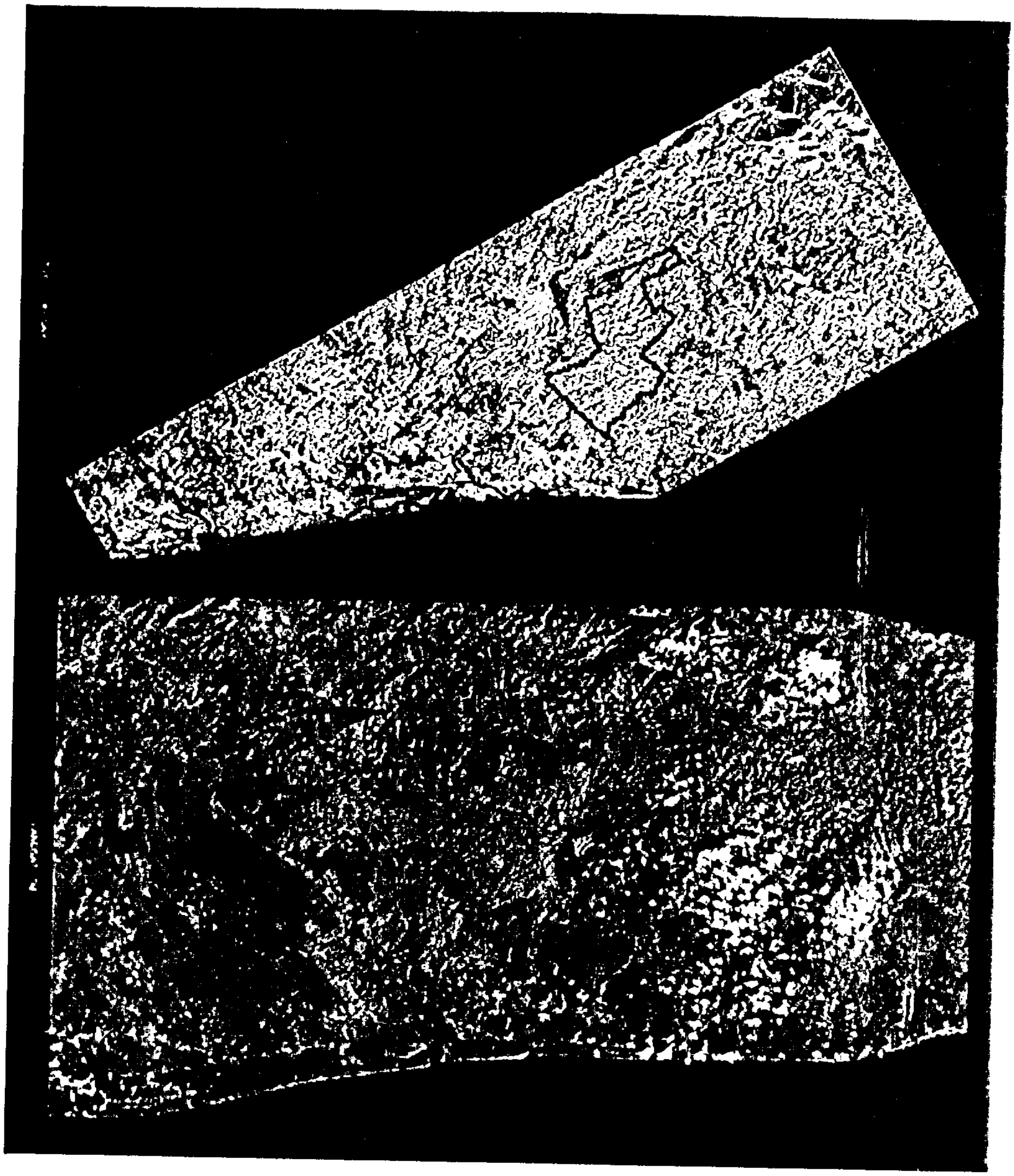
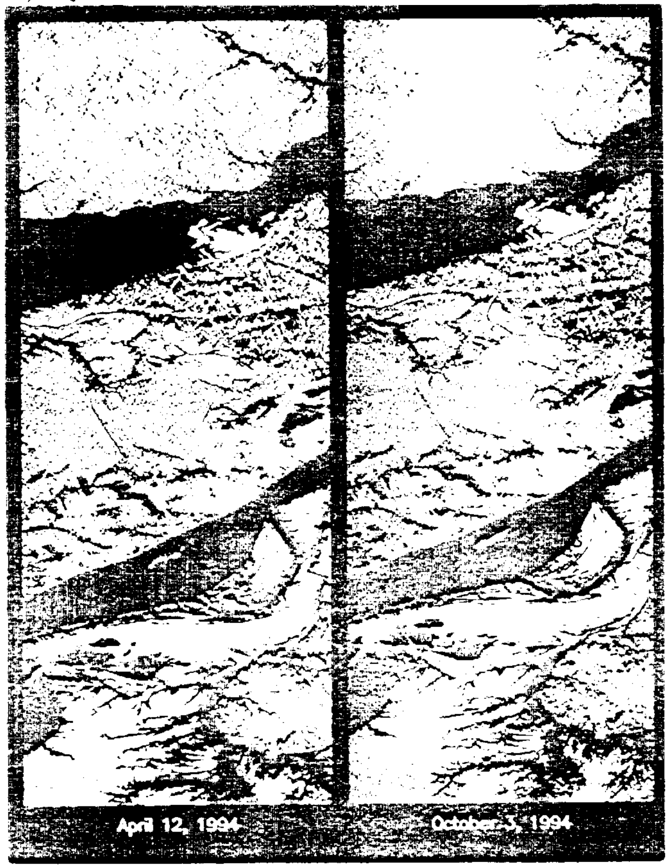


Fig. 4. Biomass regrowth of leaves, roots and wood of different aged secondary forests in tropical forests (Brown and Lugo, 1 990).




April 12, 1994
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